SEMICONDUCTORS

Effect of High Magnetic Field on Transistor Characteristics with Applications to SEU Testing

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Transistor characteristics are modified by the application of high magnetic fields. These changes are due to Hall effect voltages or magnetoresistance. Translations of device characteristics can be modeled by connecting voltage or current sources in series/parallel with the device. These translations are similar to the effect of ionizing radiation creating a plasma column in the device. This results in deterioration of device performance due to lowered noise margins in digital circuits. Because of the similarities of these effects, the magnetic field can, with some advantages, replace ionizing radiation in simulating single event upset (SEU) testing.

Results and Conclusion. The current-voltage (C-V) traces for an n-channel transistor (ECG 312) recorded at no magnetic field (B), at B of 0, 4, 8 and 10 T are shown in Figure 1. Similar results were obtained with other transistors. Observable changes in device characteristics are obtained at 4 T and above for all transistors tested. Deviation in C-V curves is a function of magnetic field strength. Increasing the magnetic field strength causes a downward shift of the C-V curve.

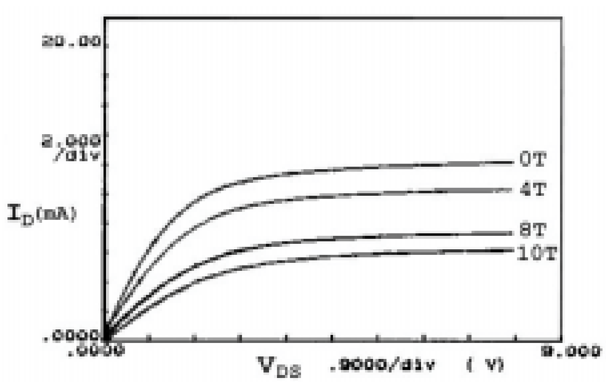

Figure 1. Current-voltage (C-V) characteristics of n-channel MOSFET recorded at V_G = 0V and varying magnetic field strengths.

In conclusion, measurements of transistor characteristics were performed under application of high magnetic fields. In these experiments we observed considerable deviations of transistor current-voltage curve when high magnetic fields are applied. The changes in device characteristics are due to either Hall effect voltages or magnetoresistance. These changes can be exploited for simulation of the effect of ionizing radiation on circuit performance.

Further work is recommended to obtain additional measurements and device parameters. The next step is to measure the performance of select integrated circuits, i.e. flip-flops, SRAM, under the influence of applied magnetic fields and compare results to identical circuits tested under ionizing radiation.

Scaling Theory of Two-Dimensional Metal-Insulator Transitions

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Ever since the development of the scaling theory of localization[1] in 1979, it has been widely believed that even a small concentration of impurities would be sufficient to localize all the electrons at T=0 in one and two dimensions, and a true metal-insulator transition would exist only in three dimensional systems. Furthermore, early experiments on electrons constrained to move on an interface between two semiconducting layers (the so called metal-oxide-semiconductor field-effect-transistors or "MOSFETs") seemed to confirm this picture. Very recently, some very exciting new developments seemed to suggest that these long-held beliefs may be incomplete. In 1995 Sergey Kravchenko and his collaborators[2] reported measurements on high mobility (fewer impurities) MOSFETs, that challenged the views[1] of the "gang of four," presenting convincing results suggesting the existence of a T=0 metal-insulator transition in this two dimensional system. For almost three years following the first report, however, the claims[2] of Kravchenko *et al*. have been met with much disbelief and few researchers have paid much attention. This skepticism has been partly based on the fact that for several years Kravchenko *et al.* were the *only* group to report such findings, as well as due to their disagreement with well accepted theoretical ideas. Very recently, the basic scaling ideas were reexamined[3] by Dobrosavljevic, Abrahams, Miranda, and Chakravarty, suggesting that for interacting electrons no fundamental principle requires the absence of a true metal-insulator transition in two dimensions. Their scaling analysis also explained several puzzling features of Kravchenko's data, strongly suggesting that a genuine transition can take place in MOSFETs. At about the same time, new experimental results were reported[4] by Popovic *et al.*, confirming Kravchenko's findings on different samples. In this work, Popovic *et al*. also demonstrated[4] that the transition can exist only in *clean enough* samples, resolving the discrepancy of Kravchenko *et al*. and the results of earlier studies done on much dirtier samples. Although at present little doubt remains that the observed transition is a genuine one, its microscopic origin remains to be established. From the experimental side, several important clues have already emerged. First, simple estimates show that the Coulomb energy is as much as *ten* times larger than the Fermi energy in the transition region—emphasizing the role of electron-electron interactions. Second, the application of magnetic fields parallel to the interface can completely suppress the metallic behavior—emphasizing the key role of the spin degrees of freedom. In the coming period, we will continue the theoretical investigations of the metal-insulator transition in two dimensions, using lessons that we have learned from both the scaling formulation[3] of the problem, as well as from the recently developed microscopic approaches[5] for disordered interacting electrons.

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Microwave Response of a Quantum Hall System

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Low-energy collective excitations in a quantum Hall system both in the bulk and at the edges of the quantum fluids are of intense current interest.[1] In particular their electrodynamical response to a high frequency (ω) finite wavevector probing field is believed to yield information complementary to standard DC transport measurements, for example on the internal structure of the edge states. The relevant energy of these excitations is dictated by the Coulomb interaction, and is typically in the range of 1 to 10 K.

We measure the photoresistance[2] of a quantum Hall system under the illumination of microwaves. Our samples are high mobility ($\mu = 3 \times 10^6$ cm^2/Vs), high electron density ($n = 2 \times 10^{11}$/cm^2) AlGaAs/GaAs heterostructures having either a standard Hall bar pattern or a surface grating geometry. Coherent millimeter wave radiation from a solid state source of tunable frequency $f = \omega / 2\pi$ from 30 to 100 GHz (1.5 to 5 K) is guided via an oversized waveguide to the sample, which is immersed in a ^{3}He liquid at a temperature ranging from 0.5 to 1.5 K.

Distinct cyclotron and magnetoplasmon resonances[2] in a low magnetic field have been observed in the experiments. Our present efforts center on the measurements at a high magnetic field up to 33 T to study the microwave responses in the fractional quantum Hall effect.

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Magnetic-Field Induced Localization of Carriers in $Al_{0.25}Ga_{0.75}As$/AlAs Multiple-Quantum-Well Structures

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We have carried out a magneto-PL study of several $Al_{0.25}Ga_{0.75}As$/AlAs structures. The lowest-energy interband transition in this system is type-II, and involves electrons occupying the AlAs X-valley minima and holes confined in the $Al_{0.25}Ga_{0.75}As$ layers. The intensity of this transition has been measured as a function of applied magnetic field (0 - 30 T) at temperatures ranging from 2.1 to 10 K. A summary of the results for a (5nm/10nm)$_{20}$ structure is shown in Figure 1, in which we plot the intensity ratio I_B/I_o as a function of applied magnetic field for various temperatures. Here I_B and I_o are the intensities of the lowest interband transition at a magnetic field *B*, and at zero magnetic field, respectively. The field was applied perpendicular to the structure's layers. At T = 2.1 K the intensity ratio drops significantly as *B* is increased from 0 to 10 T. This is in contrast with the behavior in type-I systems, in which I_B/I_o increases with increasing magnetic field. When the magnetic field is applied parallel to the layers, no change in I_B/I_o is observed. As the temperature is increased, the decrease in I_B/I_o becomes less and less pronounced and totally disappears above 10 K.

The results of Figure 1 are understood as follows: The lowest interband transition in the $Al_{0.25}Ga_{0.75}As/AlAs$ system is type-II with electrons and holes on either side of the heterointerfaces. The electron and hole wavefunctions can overlap only when their respective coordinates (x_e,y_e) and (x_h,y_h) in the xy-plane coincide. In this case the wavefunction of either carrier has an exponential tail along the z-axis that penetrates into the layer in which the other carrier is confined. If electrons and holes become localized at different points on the $Al_{0.25}Ga_{0.75}As/AlAs$ interface the wavefunction overlap will be very small or zero. This mechanism explains the substantial drop in the intensity of the type-II luminescence features when the magnetic field is along the z-axis. It is also consistent with the fact that when the magnetic field is applied in the xy-plane no significant change in the luminescence intensity is observed. The results discussed above indicate that the application of strong magnetic fields is a powerful technique that can be used to study recombination processes in type-II heterostructures.

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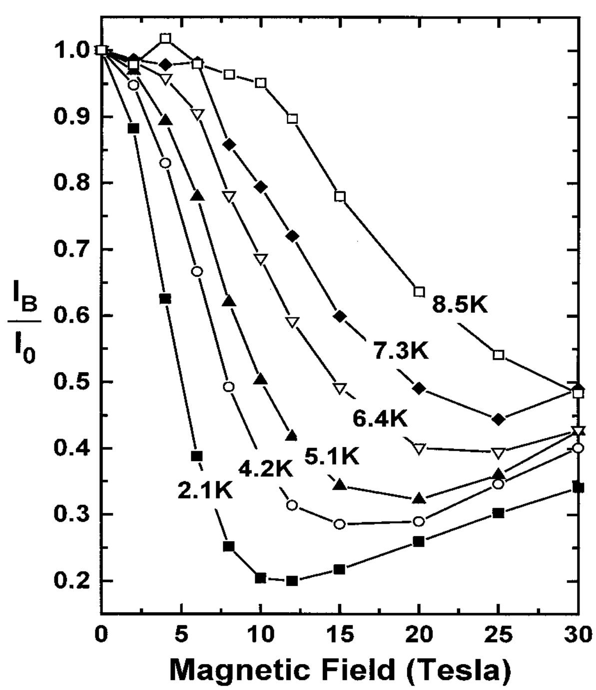

Figure 1. Luminescence intensity of the transition $X_{xy}h_1$ vs. applied magnetic field for various temperatures.

High Field NMR Studies of Photodarkening in Glassy As_2S_3 at 77 K

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All chalcogenide glasses exhibit a shift of the optical absorption edge to lower energies upon excitation with light of energy near the band edge.[1] This effect, which is known as photodarkening, can be partially annealed by thermal cycling near glass transition temperature. Even though several models[2,3] have been proposed to explain the microscopic origin of this effect, there is little experimental evidence validating or refuting these models. One of the important experimental questions is whether the photodarkening effect is associated with major structural changes in glassy As_2S_3. If photodarkening in As_2S_3 involves changes in As-S bonds, then the symmetry of the electric field tensor at the As sites will also change. Recently we have developed a technique[4,5] to characterize broad NMR lineshapes at high magnetic fields. The NMR lineshape of chalcogenide glasses at high fields depends on the asymmetry parameter (a measure of the symmetry of the electric field gradients), which in turn is sensitive to the local structural order. We measured the NMR lineshape of light soaked As_2S_3 (illuminated for ten hours by Argon laser at wavelength 514.5 nm) at 77 K. We compared this lineshape to the NMR lineshape of annealed As_2S_3 sample at 77 K. The two lineshapes were identical within the experimental error. This is a clear indication that at least in stoichiometric composition of As-S glasses (As_2S_3), there are no major structural changes associated with the photodarkening effect.

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Dry and Wet Etch Processes for NiMnSb Heusler Alloy Thin Films

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Ferromagnetic thin films and multilayers are currently being used in various magnetic recording and non-volatile memory applications. Interest in these materials for microelectronic applications has increased dramatically since the discovery of giant magnetoresistance (GMR) in multilayers comprised of alternating ultrathin (10 to 50 Å) ferromagnetic/noble metal layers.[1] Briefly, the GMR effect can be understood in terms of spin-dependent scattering of conduction electrons within the ferromagnetic layers and/or at ferromagnetic/non-magnetic interfaces. Given a difference in resistivity between spin-up and spin-down electrons ($\alpha = \rho\uparrow/\rho\downarrow \neq 1$), the resistance of the multilayer can be varied by changing the relative magnetic orientation of the ferromagnetic layers within an electron mean free path.[2] Ideally, this spin-selectivity would be infinite, so that complete control over spin-currents in magnetic devices could be achieved. This can be realized in principle in so-called half-metallic materials that are metallic for one spin type and insulating (or semiconducting) for the other. While a number of ferromagnetic half-metals have been predicted based on band structure calculations, there has not been straightforward experiments that demonstrate this behavior.[3,4] The Heusler alloy NiMnSb is a strong candidate for useful half-metallic behavior, due to its high Curie temperature (720K).[5] Recently, significant experimental effort has been expanded to deposit high-quality thin-films of NiMnSb for magnetoresistive applications. The spin filtering effect of NiMnSb thin layers will be maximized when the current flows normal to the layer plane, either resistively or by tunneling through an oxide barrier such as Al_2O_3. Therefore, the fabrication of small, high-quality etched patterns is particularly important to the potential application of these films. In this paper, we report on the plasma etching of sputter-deposited NiMnSb thin films, and on selective wet and dry etch processes for NiMnSb and Al_2O_3 structures.

A variety of plasma etching chemistries were examined for patterning NiMnSb Heusler alloy thin films and associated Al_2O_3 barrier layers. Chemistries based on SF_6, Cl_2 and BCl_3 were all found to provide faster etch rates than pure Ar sputtering. In all cases the etch rates were strongly dependent on both the ion flux and ion energy. Selectivities of ≥ 20 for NiMnSb over Al_2O_3 were obtained in SF_6-based discharges, while selectivities ≤ 5 were typical in Cl_2, BCl_3, and CH_4/H_2 plasma chemistries. Wet etch solutions of HF/H_2O and $HNO_3/H_2SO_4/H_2O$ were found to provide reaction-limited etching of NiMnSb that was either non-selective or selective, respectively, to Al_2O_3.

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Studies of High-Field Fermi-Edge-Induced Magnetoluminescence in Pulsed Magnets

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The newly established optical spectroscopy facility at NHMFL-LANL has made possible for us to study high-field optical properties of GaAs/AlGaAs heterostuctures in a pulsed magnetic field. Our experiments have focused on the study of the Fermi-edge-induced magnetophotoluminescence in a single heterostructure containing a dense two-dimensional electron gas (2DEG) in the extreme quantum limit. Simultaneous magnetotransport studies have also been conducted to characterized the corresponding electronic transport properties of the samples. For this type of heterostructure, the Fermi level of the 2DEG is very close to the second subband energy level, which allows extremely efficient coupling of the band-edge emission to the 2DEG as the Fermi sea participating in the many-body luminescence process. We have found a very interesting and anomalous effect in the emission spectra. At low magnetic fields, the emission peak does what is expected: There is a plateau in the energy position and a minimum in the intensity as the integer number of Landau levels is filled. There is, however, an unexpected peak starting to emerge at about 30 T corresponding to a filling factor $\nu = 3/2$ (see Figure 1). The new peak energy position is about 10 meV lower than that given by the normal band-edge emission, and the energy position of the new peak demonstrates an anomalous diamagnetic shift even at such high fields. In our knowledge this type of behavior in magnetoluminescence has not been observed in lower field studies reported in the literature. Further, following the development of the new peak, we found the peak has a sharp minimum in the intensity and a plateau in the energy position at $\nu = 1$. Our data analysis suggests that there is a phase transition from free-carrier-like to excitonic radiative recombination at a critical magnetic field. The experiment demonstrates that the complete lack of screening of the excitonic binding by the 2DEG for $\nu < 3/2$ in the quantum Hall regime.

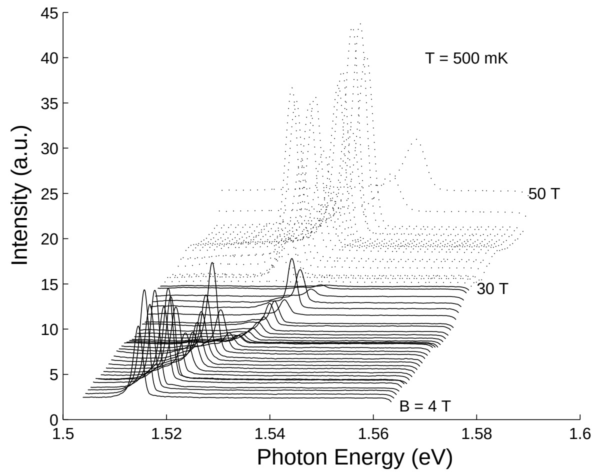

Figure 1. Luminescence spectra of a high density ($n = 9.3 \times 10^{11}/cm^2$) GaAs/AlGaAs heterostructure at different magnetic fields. Note the abrupt appearance of a new peak for $B > 29$ T.

High Rate Dry Etching of $Ni_{0.8}Fe_{0.2}$ and NiFeCo

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Thin films of NiFe and NiFeCo are commonly used in magnetic devices such as read/write heads, sensors, non-volatile memories and microactuators.[1] A general problem with these materials is that they are relatively inert in conventional plasma processes,[2-6] and thus alternative methods such as ion milling, lift-off, or electroplating have been employed for pattern transfer.[7,8] As the areal recording density of magnetic read/write heads increases toward 10 Gbit·in^{-2}, the heads will need to have sub-micron track widths.[8]

At these dimensions it is imperative to have smooth anisotropic feature sidewalls, and a drawback with simple ion milling processes is that redeposition on the sidewalls may occur. Furthermore, mask erosion due to the low etch selectivity may produce sloped sidewalls and trenches or notches at the base of etched features. The etch rates of Fe-containing alloys may be increased by elevating the sample temperature during plasma exposure,[3] but this is undesirable in manufacturing applications due to difficulties in process repeatability and may not be possible with some magnetic materials due to thermal stability concerns.

A Cl_2/Ar plasma chemistry operated under Electron Cyclotron Resonance (ECR) conditions is found to produce etch rates for NiFe and NiFeCo of ≥3,000 $Å \cdot min^{-1}$ at ≤80°C. The etch rates are proportional to ion density and average ion energy over a fairly wide range of conditions. Under the same conditions, fluorine or methane/hydrogen plasma chemistries produce rates lower than the Ar sputter rate. The high ion current under ECR conditions appears to balance $NiCl_x$, $FeCl_x$ and $CoCl_x$ etch product formation with efficient ion-assisted desorption, and prevents formation of the usual chlorinated selvedge layer that requires elevated ion etching conditions. Post Cl_2-etch removal of surface residues is performed with an in-situ H_2 plasma exposure.

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Study of Two Dimensional Electron System Under Pressure

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We have made a detailed study of magnetotransport properties of high mobility GaAs/AlGaAs heterostructure up to 15 kbar of hydrostatic pressure. Because of its relatively modest *g*-factor (g = -0.44) in GaAs, it may be possible to reduce the magnitude of the *g*-factor and quench the Zeeman energy, $g\mu_B B$, experienced by electrons in high magnetic fields. Previous study has shown that enhancement of the $\nu = 4/3$ fractional quantum Hall effect (FQHE) under pressure may be attributed to the pressure-induced reduction of *g*-factor in GaAs/AlGaAs heterostructure.[1]

In our study of two dimensional electron system under high pressures, we have focused on the spin transition observed at $\nu = 2/5$.[2] The $\nu = 2/5$ FQHE is found to gradually disappear and then subsequently reappear under increasing pressure. At pressures slightly above the critical pressure necessary for the collapse, suppression of the $\nu = 2/5$ FQHE state may be induced by tilting the sample relative to the external magnetic field. At pressures slightly below the critical pressure, rotation of the sample is found to enhance the $\nu = 2/5$ FQHE. These results suggest that the $\nu = 2/5$ FQHE exhibits a transition from a spin-polarized ground state at low pressures to a spin-unpolarized one at high pressures. Measurement of the energy gap of the $\nu = 2/5$ FQHE reveals a minimum around 13.8 kbar of pressure. The minimum in the energy gap is consistent with competition between spin-polarized and spin-unpolarized ground states as the total Zeeman energy is varied by pressure and tilting.

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Magnetoluminescence Studies of Skyrmion-Hole Transitions of a Modulation-Doped GaAs/AlGaAs Single Heterojunction

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Nonlinear optical transitions of semiconductor heterostructures in energy and intensity, which occur at integer and fractional quantum Hall states, continue to be of current interest. Magneto-photoluminescence (MPL) of a high mobility, modulation-doped, GaAs/AlGaAs single heterojunction has been studied in fields to 50 T using a short-pulse magnet in the temperature range of 0.4 K to 4 K. Simultaneous transport data taken under laser illumination showed that the sample had an electron density of about 2×10^{11} cm^{-2} in the first subband (E0); the second subband (E1) was empty. At T = 4 K, from 0 T to 5T the MPL data displayed both E1-HH and E0-HH magneto-exciton transitions. At 0.5 K, the spectrum was dominated by a single E1-HH magneto-exciton transition. Above 4 T, this magneto-exciton peak rapidly lost intensity and a new peak from the lowest 0-0 band-to-band Landau level transition appeared at a lower energy (Figure 1). Circular polarization analysis showed that this was a spin-up transition. Between 4 T to 8 T, the band intensity increased and decreased. At 8 T, close to filling factor $\nu = 1$, this spin-up transition disappeared and was replaced with a red-shifted L-L excitation with spin-down polarization.

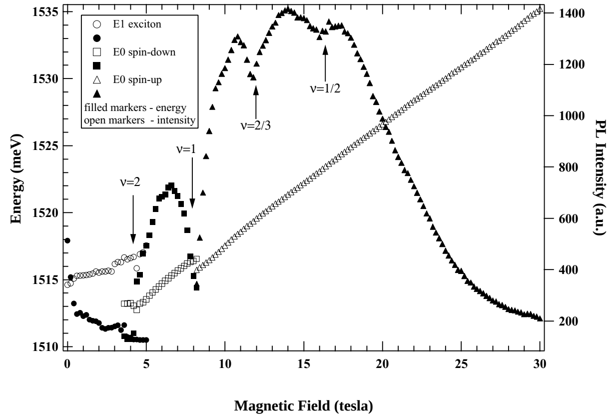

Figure 1. Magnetic field vs. PL transition energy and intensity at T = 0.5 K. Below 4 T, E1-HH exciton transition is dominant. Around 8 T ($\nu = 1$), E0-HH free carrier transition shows spin splittings. Fractional quantum Hall states are observed at around 12 T ($\nu = 2/3$) and 16 T ($\nu = 1/2$).

Its intensity rapidly increased and showed marked oscillatory behavior at various fractional quantum Hall states. Above 20 T, the intensity slowly diminished and approached a constant value whereas the energy shift of the peak remained approximately linear to the maximum field (50 T). To account for this behavior, Skyrmion-hole recombination is considered.[1-3]

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Magnetoluminescence Studies of Quantum Wells and Quantum Wire Superlattices

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We studied diamagnetic shift and Zeeman splitting in $GaAs/Al_{0.25}Ga_{0.75}As$ single quantum wells (SQWs) by photoluminescence (PL) and PL excitation (PLE) in strong magnetic field. The diamagnetic shift monotonically decreases as QW width (L_z) decreases, which contradicts with other previous reports showing minimum at the vicinity of L_z where the binding energy becomes minimum (Lo). Our results have been interpreted with the effective mass model and the dimensionality of the 2-D confined exciton. The discrepancy between our results and the others is believed to be related to the scattering caused by the heterointerface roughness. Also, a drastic change in diamagnetic shift that is theoretically expected in the exciton decoupling due to Landau splitting could not be observed. Zeeman splitting has also been measured on these samples in the polarization dependent PL. The analysis of Zeeman result is still in progress, and the results will be submitted for publication in near future.

The magnetoluminescence has been performed with quantum wire (QWR) superlattices of several wire-widths, while applying the field in parallel to the growth direction and angled geometry. The samples used in this work are $GaAs/Al_{0.5}Ga_{0.5}As$ QWR superlattices whose lateral periods are 8 nm, 16 nm, 32 nm. They have been prepared by migration enhanced epitaxial method (MEE) on vicinal GaAs substrate toward [110].

The diamagnetic shift of QWRs in low magnetic field intensity are well fit to the quadratic relation of the field. This can be interpreted with an 2-D excitonic model based on the inter-wire coupling of electron and hole, and it can be understood with the electronic wave-function spread over neighboring wires in the QWR of narrow wire-width (the period of 8 nm). However, the exciton formation in QWRs of relatively broad wire-width (16 nm or larger) is dominated by intra-wire coupling, which has typical 2-D nature.

When a strong magnetic field is applied to QWR superlattice, the cyclotron motion competes with the 1-D quantum confinement in narrow wire-width QWR superlattice. If the cyclotron diameter becomes comparable or larger than the QWR period, the quantum fluctuation effect has been detected. This kind of phenomena has not been reported. The publication is in preparation.

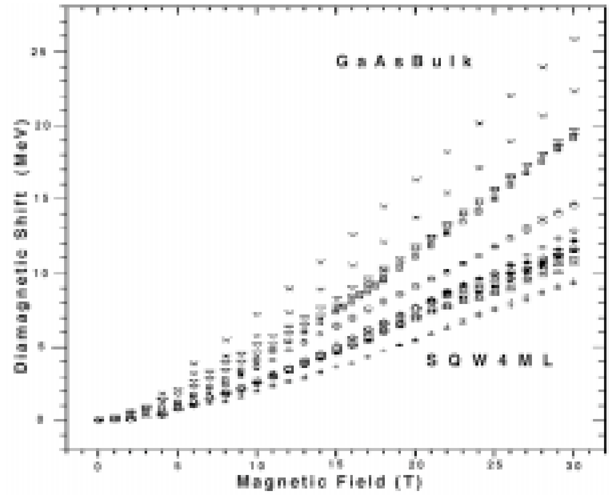

Figure 1. Diamagnetic shift of GaAs/AlGaAs SQWs.

Magnetotransport Characterization of a Low-Temperature-Grown GaAs Heterostructure in Pulsed Fields

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A new class of semiconductor grown by molecular beam epitaxy has attracted much of the recent attention. It has been found a thin layer of GaAs grown under relatively low temperature (LT) (~ 400˚C) can produce very short carrier lifetimes which is a promising property for ultrafast electronics. We have recently fabricated a LT-GaAs/AlGaAs heterostructure under this growth condition. We have found that the density of this structure (~ $10^{13}/cm^2$) is about 15 times higher than that in a conventional heterostructure with same amount of donors. We believe this unusually high density is due to the large number of impurity (or trap) states provided by the non-crystalline LT-GaAs host materials for the two-dimensional electron gas.

Since there are large number of filled levels contributing from different subbands at low-fields, to characterize the transport properties of such high-density structures, very high field is required. We have performed a magnetotransport experiment in the pulsed magnet. Based on the Shubnikov-de Haas oscillations in the transport data, we have been able to determine that as many as five subbands are filled in this structure. Furthermore, we have also been able to estimate the populations in each level individually. We believe this type of heterostructure not only provides an experimental system to study the basic physics in the regime where the Coulomb interaction is extremely strong, but also has potential for new devices.

Microwave Resonance in High B Insulating Phase of Two-Dimensional Hole System

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As magnetic field, B, is swept up, a two-dimensional electron or hole system (2DES or 2DHS) of sufficiently low disorder exhibits a series of fractional quantum Hall effect (FQHE) states, and then undergoes a transition to an insulating phase. At high enough B, the ground state of a two-dimensional system without disorder is expected to be a Wigner crystal (WC). We have studied[1] the microwave conductivity in the high B insulating phase of a high quality 2DHS, and observed a resonance in the spectra, which we obtain as the real part of diagonal conductivity ($Re(\sigma_{xx})$) vs. frequency (f). Such microwave resonances in insulating phases have been observed as well in 2DES,[2,3] and are usually interpreted as due to a pinning mode, in which the WC oscillates in the potential of the impurities that pin it. The peak in $Re(\sigma_{xx})$ vs. f in the high B insulator is discernible for $\nu < 0.30$. The frequency of the peak, f_{pk}, increases with B, but becomes nearly flat for B > 10 T ($\nu < 0.22$), with f_{pk}~1.25 GHz. S, the integrated $Re(\sigma_{xx})$ vs. f, is likewise nearly B independent in that region. The plots of S and f_{pk} vs. B, taken together, conflict with the standard classical oscillator model of the resonance as a mode of a disorder-pinned WC. The resonance Q, defined as f_{pk} divided by the full width at half maximum, increases linearly with B throughout the range where the resonance is observed, and is about 5 at our maximum B of 15.5 T to date. The sharpness of the line is surprising for a mode which has its origin in pinning by random impurities. Future studies will extend this work to higher magnetic fields.

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High-Field Magnetospectroscopy of InAs/$Al_xGa_{1-x}Sb$ Single Quantum Wells

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There is considerable interest in the electronic properties of InAs/$Al_xGa_{1-x}Sb$ type-II heterostructures because of their unusual band-edge alignment, which can result in spatially separated electrons and holes confined in adjacent layers. We have recently attributed features (e-X and h-X lines) observed in far-infrared (FIR) magneto-transmission experiments on InAs/$Al_xGa_{1-x}Sb$ single quantum wells at low magnetic fields to internal transitions of stable excitons.[1] We have extended these measurements to 30 T to probe effects of the magnetic-field-induced semimetal-semiconductor (SM-SC) transition, and to achieve a better understanding of the so-called conduction-valence Landau-level mixing (CVLLM) effect[2] on the hole (in barrier) and electron (in well) states.

Far infrared magnetotransmission results for a single InAs 15 nm quantum well with barrier x = 0.1 are shown in Figure 1; the spectra and their evolution with field are very complex. The line labeled e-CR is electron cyclotron resonance from the lowest spin-up Landau level (0,↑) to (1,↑). The e-X and hX lines, whose strengths show very similar temperature and field dependence, persist to about 15 T. A new feature, Y, appears about 30 cm^{-1} below e-CR at magnetic fields above 13 T, narrows and gains strength with increasing magnetic field up to 16 T, loses intensity at still higher fields, and is not observable above 23 T. The Y feature appears to be spin-down (0,↓) -(1,↓) CR; its behavior with field is qualitatively consistent with the recent CVLLM calculations.[2] Near 23 T (filling-factor ~ 1) another line appears. Above 27 T only the higher frequency line survives. The existence of two lines for $23 < B < 27$ T (filling factor < 1) is not understood. The initial increase in strength and subsequent decrease above 12 T of the e-X and h-X lines, and their observed decrease in strength with increasing

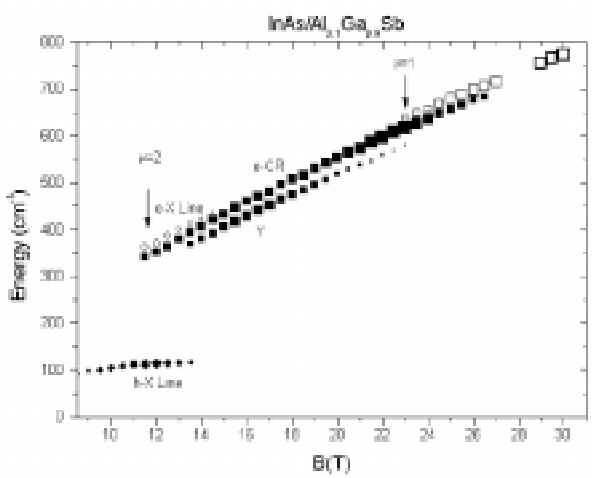

Figure 1. Photon energies of the transmission minima for CR-like features (squares), e-X (open circles) and h-X (solid diamonds) are plotted versus magnetic field. The area of the symbols indicates the relative strength of the various features; the h-X line has been scaled up by a factor of 4. The field positions for filling-factors 2 and 1 are indicated by the arrows.

temperature are consistent with both being internal transitions of the same bound state (an exciton-like state in the presence of excess electrons). Detailed understanding of these features awaits completion of self consistent calculations including charge transfer effects at high fields.

The behavior of the e-X and h-X lines is consistent with occurrence of multiple magnetic-field-induced SM-SC transitions (the lowest occurs near 16 T to 18 T; the final transition, when the (0, ↑) electron LL crosses the (0, +3/2) hole LL, occurs at 28 T) and their assignment to internal transitions of stable, spatially separated excitons in the presence of excess electrons.

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Skyrmions in the Integer and Fractional Quantum Hall Effect

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Recent experiments[1] have confirmed the theoretical expectation[2] that the elementary excitations of the $\nu = 1$ integer quantum Hall effect are topologically nontrivial spin textures called skyrmions. The size of the skyrmion is determined by two competing energy scales: the Zeeman energy ($g\mu B$), which favors the least number of spin flips; and the Coulomb exchange energy ($e^2/\varepsilon l_0$), which prefers to have neighboring spins as parallel as possible. As one varies the ratio of these two energy scales (e.g., by tilting the sample) the size of the skyrmion, or more specifically the number of spin flips involved, changes.

Using recently proposed[3] "quantum" skyrmion wave functions we have studied these excitations using both variational Monte Carlo and a recently developed ‘fixed-phase’ diffusion Monte Carlo method.[4] Figure 1 shows results of our calculations of the energy gap (the energy for creating a skyrmion-antiskyrmion pair) as a function of for $\nu = 1$.[5] Each line segment corresponds to a given number of total spin flips. Results are shown for the pure Coulomb interaction ($\beta = 0$) and for the case when the finite “thickness” of the two dimensional electron gas is taken into account ($\beta = 1l_0$). The results clearly show the importance of taking the effect of finite thickness into account.

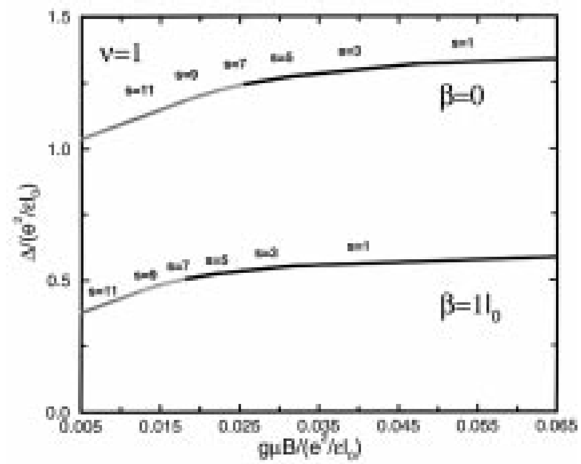

Figure 1. Activation energies for skyrmion-antiskyrmion pairs with different spins (s) and at different thicknesses (β) as a function of $\tilde{g}$.

Figure 2 shows “fixed-phase” diffusion Monte Carlo results for the excitation energy of a single “antiskyrmion” at $\nu = 1$. These results demonstrate the importance of including the effect of higher

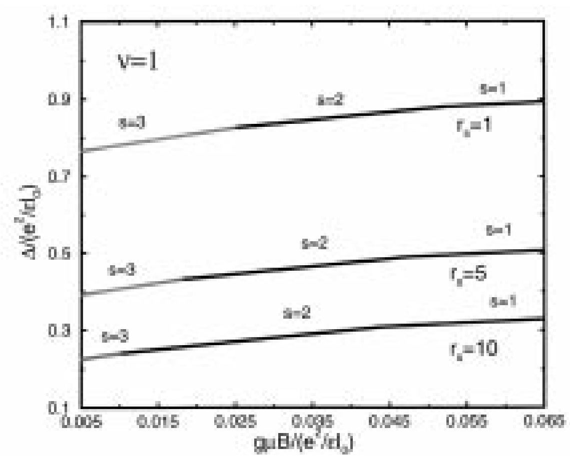

Figure 2. Activation energies for spin-reversed quasielectron-antiskyrmion pairs with different spins (s) and at different values of the electron gas parameter r_s as a function of $\tilde{g}$.

Landau levels (Landau level mixing is characterized by the electron gas parameter r_s. The results we have obtained agree reasonably well with experiment.[5] In addition to this, we have also studied the possibility of the existence of skyrmions in the *fractional* quantum Hall effect. Preliminary results suggest that the fields necessary for skyrmion physics to appear at $\nu = 1/3$ is extremely small.

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Quantitative Study of Large Composite-Fermion System

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It has only recently become possible to make quantitative calculations using the composite fermion wave functions proposed by Jain[1] nearly eight years ago. For the “parent” quantum Hall states, those with filling fraction $\nu = 1/m$ where m is an odd integer, the required Landau level projection can be performed (up to a final step) analytically and the results compared with the trial states proposed by Laughlin.[2] The good agreement shows that these two approaches are, for all intents and purposes, equivalent.

To go beyond the parent states Jain and Kamilla[4] have introduced modified composite fermion wave functions describing the fractional quantum Hall states at filling fractions $\nu = p/(np+1)$ where p = 1, 2, 3... and n = 2, 4,.... These wave functions, which are both fully projected into the lowest Landau level and suitable for numerical study, have been used to perform *quantitative* calculations of the energy gaps for the fractional quantum Hall hierarchy. In order to make direct comparison with experiment the effect of the finite thickness of the 2DEG has been included in the calculation. We have also studied the effect of Landau level mixing on these states by applying the "fixed-phase" diffusion Monte Carlo method.[4] The results allow for arguably the first *quantitative* comparison of the composite fermion theory of the fractional quantum Hall hierarchy with experiment.

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Cyclotron Resonance of $Zn_{1-x}Cd_xSe$ Heterostructures

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This report is on the effective mass of the two-dimensional electron gas (2DEG) structures based on modulation doped $ZnSe/Zn_{1-x}Cd_xSe$ single quantum wells. These structures have shown novel phenomena in both transport[1] and coherent spectroscopy.[2] Even though there are a large number of optical studies on the ZnSe/ZnCdSe-based heterostructures motivated by their use in blue-green laser diodes, there have been no direct measurements of the cyclotron resonance in these systems. Here, we report on cyclotron resonance measurements in two such samples with x = 0.12 and 0.2 and with carrier densities of 2.0 and 4.5×10^{11} cm^{-2}, respectively. Far-infrared absorption was measured at 4.2 K and with magnetic fields up to 27 T. From the half-width of the magneto-transmission spectrum, the scattering lifetime is estimated to be ~5×10^{-13} s and the mobility of the free carriers is ≈6500 $cm^2/V\cdot s$. These values are in close agreement with the values obtained from transport measurements. Plots of the resonance frequency versus magnetic field (Figure 1) show intercepts passing through the origin, indicating a free carrier resonance and allowing the first reliable determination of the conduction band effective mass $m^* = 0.144 \pm 0.01\ m_e$) in this system. This is the first reported measurement of the effective mass for this system. The results have been submitted to *Journal of Applied Physics*.

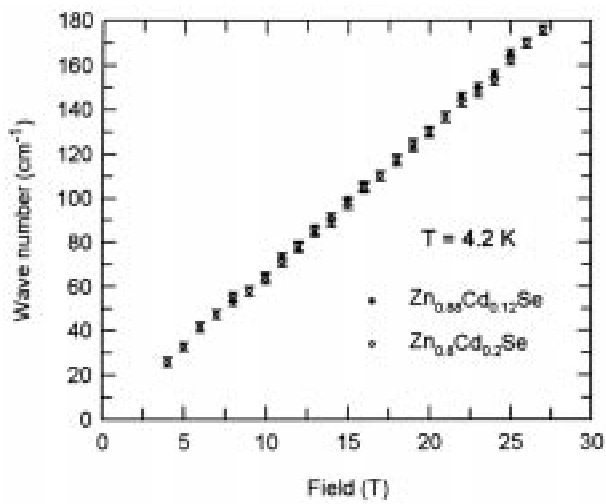

Figure 1. Cyclotron resonance frequency of $ZnCd_{1-x}Se_x$ heterostructures.

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Two-Dimensional Metal-Insulator Transition: Effects of Disorder and Magnetic Field

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Since the development of the scaling theory of localization for noninteracting electrons,[1] there has been a general belief that, in two dimensions, all states are insulating and, consequently, there is no metal-insulator transition (MIT). This belief was bolstered by early experiments[2] on low-mobility (very disordered) two-dimensional electron system (2DES) in Si metal-oxide-semiconductor field-effect transistors (MOSFETs). Recent experiments[3] on high-mobility (less disordered) Si MOSFETs have provided evidence for the existence of a true MIT in this strongly interacting electron system, raising speculation that this transition is driven by electron-electron interactions. For several years, however, those results were met with much disbelief and few researchers have paid much attention until, in spring 1997, the basic scaling ideas were reexamined[4] and it was demonstrated that for interacting electrons no fundamental principle requires the absence of a true MIT in 2D. Moreover, at about the same time, we have reported the results of our experiments[5] on a 2D MIT. These developments were followed by the "acceptance" of the existence of this transition by the solid state community, and the problem of a 2D MIT has become the topic of much interest and debate.

Our experiments were carried out on a 2DES in Si MOSFETs of Corbino geometry. Conductance was measured as a function of carrier density at temperatures $1.2 < T < 4.2$ K and magnetic fields B of up to 8 T. In these samples, all electronic states were found to be localized, in agreement with early studies.[2] By applying the substrate bias, however, we have been able to decrease the disorder scattering in our samples and observe the emergence of the metallic phase. Thus our experiment has not only provided an independent confirmation of the existence of a 2D MIT but also demonstrated that the MIT can exist only in clean enough samples, resolving the discrepancy between early[2] and more recent[3] experiments by other groups. In addition, our careful measurements of magnetoconductance in the quantum critical region in the presence of a perpendicular B field have provided quite a bit of insight into the relative importance of spin interactions and orbital motion at the MIT. In particular, we have shown that the spin-dependent part of the electron-electron interaction decreases sharply as the transition is approached from the metallic side. While the detailed mechanism of the transition remains a mystery, our results support some early theoretical ideas[6] that suggest that interactions between electrons with different spins may give rise to a metallic state at low temperatures. By extending our measurements to lower temperatures and higher magnetic fields, we hope to gain further understanding of this exciting new phenomenon.

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Magnetoluminescence Studies of a 2D Electron Gas in Diluted Magnetic Semiconductor Quantum Wells

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We have carried out a study of band-edge luminescence in a series of *n*-type modulation-doped ZnSe(Cl)/$Zn_{0.825}Cd_{0.14}$ $Mn_{0.035}Se$ single quantum wells as a function of magnetic field in the 0-30 T range. The results shown here come from a 10 nm $Zn_{0.825}Cd_{0.14}Mn_{0.035}Se$ well. The donors in the ZnSe barriers release their electrons into the magnetic well, where they form a dense (1.6×10^{12} cm^{-2}) electron gas. Excitons are screened for such high electron densities and the PL spectrum is dominated by electron-hole recombination processes. These magnetic structures differ from previously studied non-magnetic wells in one important aspect: the g-factor of the ZnCdMnSe well layer is 30 times larger than the g-factor of the non-magnetic ZnCdSe material. The magnetic splitting of the well saturates at magnetic fields larger than 10 T; the electron cyclotron gap $\hbar\omega_c$ on the other hand is a linear function of the magnetic field *B* for all field values.

At zero field the PL spectrum is broad and featureless. For low magnetic fields the PL feature shifts rigidly toward lower energies as shown in Figure 1 in which we plot the energies of the various PL components as a function of *B*. This large red shift (50 meV at 10 T) is due to the sum of the energy changes of the lowest energy (m_j = - 1/2) electron and the highest energy (m_j = -3/2) hole states. For magnetic fields B > 10 T, the PL band exhibits distinct features which are due to recombination processes among conduction band Landau levels (ℓ= 0,1,2, and 3) associated with the m_j = - 1/2 spin state and m_j = - 3/2 photogenerated holes. The dependence of Landau level population on magnetic field was used to determine the electron density in the magnetic well.

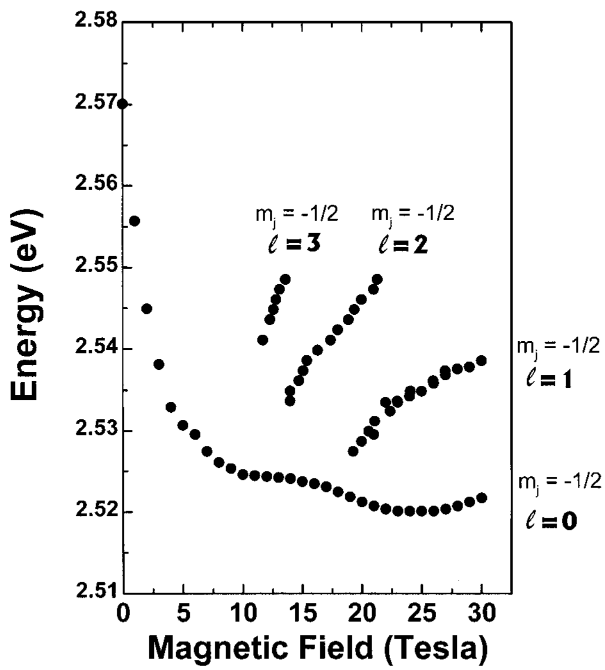

Figure 1. Plot of the energies of the various PL components as a function of magnetic field.

The physical system studied is unique because the electron spin-splitting ΔE_s is much larger than the corresponding splitting in non-magnetic II-VI and III-V structures. In addition, the saturation value (B > 10 T) of ΔE_s can be tailored by varying the Mn^{++} concentration in the wells. The relative size of the spin-splitting ΔE_s and the cyclotron gap ΔE_c at a fixed magnetic field can be continuously changed by varying the angle between the applied field with the perpendicular to the structure layers.

Comparative Study of Quantum Well Diode Lasers in Magnetic Fields

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We have recently studied the operation of blue-green diode lasers, based on II-VI semiconductor quantum well heterostructures, to investigate the high density electron-hole system that forms the optical gain in these devices.[1] Work performed at the NHMFL showed that magnetic field induced shifts in the gain spectrum of such lasers at room temperature were small (< 2 meV up to 30 T), and nearly identical to the diamagnetic shifts measured at the n=1 HH exciton absorption in the same ZnCdSe/ZnSSe single quantum well separate confinement heterostructures. These results support the idea that the large electron-hole Coulomb interaction in II-VI quantum wells maintains a predominantly pairwise correlation within the e-h system in laser device, that is, a distinctly excitonic component. The experiments were also part of a broader study by us where the effects of large magnetic fields are being investigated for different classes of diode lasers in an attempt to learn of many body effects in a dense e-h system in magnetic fields through the field induced modifications to the gain spectrum and their impact on the interband optical transitions.

In this report we highlight recent results that have been obtained on AlGaAs quantum well diode lasers (x < 0.10) in fields up to 33 T. Although some experimental reports on the behavior of the output spectra on GaAs diode lasers were published some time ago,[2] the results and their interpretation were incomplete and somewhat contradictory. The devices used by us in the present work were state-of-the-art ridge waveguide devices, mounted in a cryostat with the external magnetic field perpendicular to the QW layer plane (i.e. field parallel to current flow).

A summary of representative data is shown in Figure 1, which displays the peak energy of the lasing spectra of a diode laser device as a function of the magnetic field at three cryostat temperatures, T = 4.2 K, 77 K, and room temperature. For each temperature, the data were taken under constant current conditions, namely at I = 1.2 mA (Ith = 0.8 mA), I = 4.0 mA (Ith = 2.5 mA), and I = 45 mA (Ith = 20 mA), respectively. In order to maintain the constant current conditions over the entire field range, voltage adjustments of less than 5% were required, showing that magnetotransport effects did not significantly influence the diode laser operation.

The principal result of Figure 1 is the behavior of the laser emission spectrum at low/moderate magnetic fields. Depending on temperature, one finds an initial field regime where the shifts in lasing photon energy are nearly constant (low temperature) or subject to oscillations (room temperature). At cryogenic temperatures, an abrupt transition is found within a narrow field range (~ 1 T) beyond which an approximately linear shift is observed for subsequent fields. In contrast to room temperature measurement, where the slope of the shift approximately fits the cyclotron energy for a free electron-hole system, such

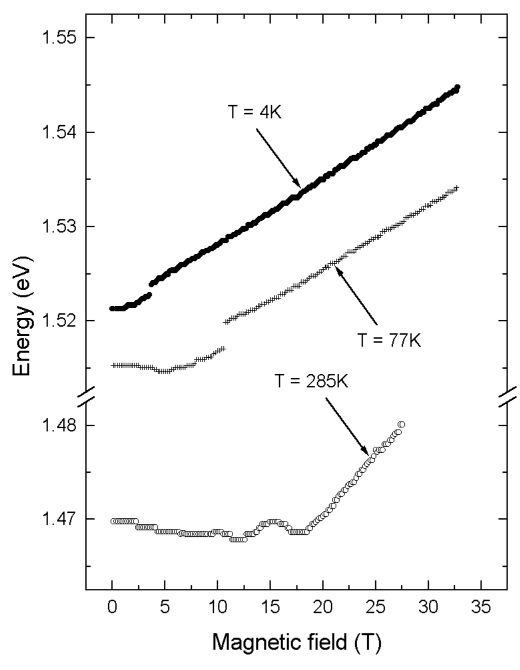

Figure 1. The emission spectra from an AlGaAs diode laser as a function of magnetic field at 4.2 K, 77 K, and 285 K, respectively.

a simple effective mass model yields larger e-h masses. At all temperatures, a simple one electron Landau-level model seems quite inadequate in the low/moderate field regime. Present efforts are directed in developing an understanding of this phenomena that appears to be a manifestation of magnetic field dependent many-body effects in the diode. While the behavior of magnetoexcitons in GaAs QWs has been studied in detail in recent experiments,[3] the pair densities are considerably higher in the present work (estimated to be approximately 10^{18} cm^{-3} in bulk equivalent units). Yet, there appears to be no available theory to address the issue of the impact of magnetic fields on exchange and correlation effects in such III-V semiconductor quantum wells, the probing of which is conveniently experimentally accessed through the use of a diode laser.

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